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COMBUSTION INSTABILITY OF SOLID PROPELLENTS : EFFECT OF OXIDIZER PARTICLE SIZE, OXIDIZER/FUEL RATIO AND ADDITION OF TITANIUM DIOXIDE TO PLASTIC PROPELLENTS

by

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SUMMARY

The effect of variations in the composition of solid propellents on their tendency to show combustion instability at 1000 psi (6895 kN/m^2) has been investigated using ~~the~~ T burner. It has been shown that ammonium perchlorate particle size can have a large effect on the acoustic response and that this is frequency-dependent. Titanium dioxide is usually added to plastic propellents to promote stable combustion and the mechanism of its action has been determined. With a view to the potential use of oxygen-balanced propellents the effect of varying the oxidizer/fuel ratio of plastic propellents has also been studied.

CONTENTS

1 INTRODUCTION

Progress in the understanding of the factors governing combustion instability in solid propellent rocket motors has been made in the last few years. It is hoped that soon it will be possible to predict the relative stabilities of burning of solid propellents in rocket motors before the actual motors are fired, on the basis of knowledge of the propellent composition and motor dimensions.

A rocket motor may be regarded as an acoustic cavity with various sources of acoustic gains and acoustic losses for each mode of that cavity. If the gains exceed the losses for a particular mode then a pressure oscillation in that mode can be amplified and will grow in amplitude until either pressures high enough to burst the motor case are developed, or until a steady maximum pressure-amplitude is maintained due to one or more of the sources of acoustic gain or loss becoming pressure amplitude dependent in such a way that gains and losses balance.

The more important sources of acoustic gain and loss are shown in Fig.1, taken from Hart[1]. The major source of acoustic energy input is the burning zone and a measure of this is given by the acoustic response μ/ε, where μ is the fractional perturbation of mass flow rate through the zone caused by a fractional perturbation of pressure, ε. In general μ/ε will be a complex quantity reflecting the difference in phase between the oscillating pressure and the resulting oscillation of mass flow rate. An important source of acoustic loss is caused by particulate damping of the acoustic waves both in the burnt-gas phase and in the flame zone. It was decided to concentrate initially on studying the above two effects at the R.P.E., and experiments have been carried out in T-burners to determine how these effects are varied by changes in propellent composition such as the ammonium perchlorate particle size and addition of titanium dioxide (TiO_2) to the propellents. TiO_2 is now generally added to British plastic propellents to promote stable combustion. All propellents discussed in this Report are based upon polyisobutene (P.I.B.) as the fuel and ammonium perchlorate as oxidizer.

Much interest has been shown recently in developing propellents giving an exhaust that is effectively free from attenuation or modulation of radio signals. The attenuation is known to be associated with the free electron concentration in the rocket exhaust jet and is therefore enhanced when secondary combustion and hence rise in temperature of the exhaust occur. One way of reducing the tendency of a rocket motor to produce secondary combustion

is to use propellents in which the oxidizer/fuel ratio approaches the stoichiometric value i.e. propellents of which the exhaust gases contain only small concentrations of the combustible gases, hydrogen and carbon monoxide. However, these stoichiometric or oxygen-balanced propellents are slightly more energetic than the usual fuel-rich propellents and concern had been expressed over the possibility that they may possess an increased tendency to combustion instability. Accordingly, the acoustic response was determined of four propellents in which the oxidizer/fuel ratio was varied. All the experimental firings were carried out at a mean pressure of 1000 psig (6895 kN/m^2) which was chosen as a typical operating pressure of modern solid propellent rocket motors. The effects of oxidizer/fuel ratio and ammonium perchlorate particle size on the acoustic response have not been studied extensively. Price at the Naval Ordnance Test Station has carried out work[2,3] using an ammonium perchlorate/polybutyl acrylic acid co-polymer (P.B.A.A.) propellent system and an operating pressure of 200 psi (1379 kN/m^2). The findings from the work now reported differ in some important respects from those of Price.

Finally, the experimentally determined response functions for two groups of the above propellents were compared with values calculated by the methods devised by McClure[4] and his co-workers at the Johns Hopkins University to determine whether theory could predict the effect of change of one specific variable.

2 THEORY

The theory of the T-burner[5,6,7] has been described elsewhere but is briefly summarized here. It has been shown that for a T-burner with propellent at both ends, the real part of the specific acoustic admittance of the burning surface, Re (Y), where Y is defined as the ratio of the acoustic velocity to the acoustic pressure, is given by

$$\mathrm{Re}\,(Y) = -\frac{L}{2\,\rho_{gas}\,c^2}\,(\alpha_g - \alpha_d) \quad . \qquad (1)$$

(The symbols are listed on p.17.)

McClure[4] has expressed the real part of the specific acoustic admittance for a propellent driving oscillations in an end-burning motor as

$$\mathrm{Re}\,(Y) = \mathrm{Re}\left[-\frac{\bar{v}}{\bar{p}}\left(\frac{\mu}{\varepsilon} - \frac{1}{\gamma}\right)\right] \qquad (2)$$

where μ/ε is the response function of the combustion zone, μ being the fractional perturbation of mass flow through the zone, and ε the fractional perturbation of pressure.

Combining (1) and (2) and introducing the further substitutions that $c = 2\,Lf$, $\bar{v}\,\rho_{gas} = r\,\rho_{solid}$, and applying McClure's correction for the mean flow in the burner, yields

$$\mathrm{Re}\left(\frac{\mu}{\varepsilon}\right) = \frac{\bar{P}}{4\,r\,\rho_{solid}\,fc}\left(\alpha_g - \alpha_d\right) \quad . \qquad (3)$$

3 EXPERIMENTAL

The T-burner[7] is shown schematically in Fig.2 and consists basically of a tube 2.0 inches (50.8 mm) in diameter closed at both ends in which the gas oscillates in the fundamental longitudinal mode. The burner tube can be varied in length by using either extension tubes or different centre pieces, so that frequencies in the range 0.7 to 4.0 kHz may be studied. An orifice, 0.5 inch diameter, located centrally in the burner tube is connected with a 4 cu ft surge tank. This prevents any appreciable change in the mean pressure during the burning and since the connection is at the centre of the tube, i.e. at a pressure node, acoustic losses are minimised. The system is pressurised with nitrogen to 1000 psig (6895 kN/m^2) before firing and the propellent ignited by small cartons containing 0.4 gm of a standard pyrotechnic composition, SR 371C. The pressure in the burner tube was measured by quartz piezo-electric pressure transducers (Kistler Instrument Corp. or Vibro-meter Corp.) and recorded photographically.

The plastic propellent used in these studies contained polyisobutene (P.I.B.) as the fuel and was mixed at the E.R.D.E. Waltham Abbey. The propellent charges were prepared by first coating the T-burner end caps with Pliobond and then pressing an accurately weighed amount of propellent, 33.4 gm, into each end cap. The thickness of the resulting disc of propellent was 0.4 inch (10.2 mm). The compositions and some of the ballistic properties of the propellents used for this work are given in Tables 1 and 2.

4 RESULTS

All the firings reported here were carried out at a mean pressure of 1000 psig (6895 kN/m^2). This pressure was chosen as being representative of most solid propellent rocket motor firings.

For each propellent the logarithmic rates of growth and decay of the pressure oscillations were plotted against frequency. Since the temperature in the burner tube was lower when the decay constants were measured than when the growth constants were measured, the decay constants were corrected to the temperature at which the growth constants were measured by the method described in an earlier report[7].

The real part of the response function, Re (μ/ε), and the real part of the specific acoustic admittance, Re (Y), were then calculated using equations (1) and (3).

The effect of particle size on Re (Y) and Re (μ/ε) has been examined both in the absence (Figs.3 and 4 respectively) and in the presence (Figs.5 and 6 respectively) of 1% of titanium dioxide (TiO_2) in the propellent. In the majority of T-burner firings a steady maximum pressure-amplitude was reached when the acoustic losses and gains for the system were balanced. This has been plotted against frequency in the absence of TiO_2 (Fig.7) and the presence of 1% TiO_2 (Fig.8).

The theoretical value of Re (μ/ε) has been calculated for the propellents not containing TiO_2 using as many experimentally determined quantities as possible (Fig.9). Further details of the calculations are given in earlier reports[7,8] and the values used in the calculations are given in Table 3.

The reduced pressure-amplitude, i.e. increased stability, resulting from the addition of TiO_2 to propellent containing fine, medium and coarse oxidizer is shown in Figs.10,11 and 12 respectively. The effect of addition of different TiO_2 percentages to the propellent on the experimental Re (Y) and Re (μ/ε) and on the theoretical Re (μ/ε) are shown in Figs.13,14 and 15.

The frequency dependence of Re (Y), Re (μ/ε) and the maximum pressure-amplitude for the group of propellents in which the oxidizer/fuel ratio was varied is shown in Figs.16,17 and 18. The dependence of the maximum pressure-amplitude on fuel/oxidizer ratio at specific frequencies is given in Fig.19. Fig.20 shows the theoretical flame temperature and specific impulse of the propellents used in Figs.16-19.

5 DISCUSSION

5.1 Effect of variation of ammonium perchlorate particle size

The propellents used for this section of the research are split into two groups: first, propellents F, D and E in which the oxidizer particle

size was varied for a propellent containing 88% ammonium perchlorate and 12% USB2 (90% polyisobutene + 10% S101 wetting agent), and second, propellents I, C, J in which the oxidizer particle size was again varied for propellents containing 87% ammonium perchlorate, 12% USB2 and 1% titanium dioxide. There is a slight change in the oxidizer/fuel ratio between the two groups of propellents but other experiments (section 5.4) have shown that this small change has little effect on the acoustic response or any other associated property.

Table 1 shows that, as the oxidizer particle size is reduced, the experimental linear burning rate of the propellents under steady state conditions increases, as predicted by Nachbar[9]. This is observed for both groups of propellents and the percentage change as the oxidizer particle size is reduced is similar in each group.

Considering now the tendency of the propellents to burn unstably, Fig.4 shows that as the frequency increases, the real parts of the acoustic response for the three propellents F, D and E all tend towards the same value (~1.0). This indicates that at high frequencies, Re (μ/ε) is independent of oxidizer particle size and any change in the relative stability of burning stems solely from a change in the steady state burning rate, as shown in equation (6).

The admittance of a solid propellent burning zone is given by

$$Y = -\frac{\bar{v}}{\bar{p}}\left(\frac{\mu}{\varepsilon} - \frac{1}{\gamma}\right) , \qquad (4)$$

which may be written as

$$Y = -\frac{\bar{m}}{\rho_{gas}\,\bar{p}}\left(\frac{\mu}{\varepsilon} - \frac{1}{\gamma}\right) \qquad (5)$$

or

$$Y = -\frac{\bar{m}}{\bar{p}^2} \cdot \frac{RT_f}{M} \cdot \left(\frac{\mu}{\varepsilon} - \frac{1}{\gamma}\right) , \qquad (6)$$

showing that for a constant pressure and acoustic response the acoustic admittance is directly proportional to $\left(\bar{m} \cdot \frac{RT_f}{M}\right)$, which is a measure of the rate of heat release of the propellent. This is the quantity responsible for the differences in the admittances of propellents D, E and F at high frequencies.

At the lower frequencies, Re (μ/ε) decreases with a decrease in the oxidizer particle size, but the burning rates act in the opposite direction resulting in the admittance of the three propellents all being similar.

The pressure exponent n in the burning rate law

$$r = a P^n . \tag{7}$$

has been shown to be similar for all the propellents considered in this Report, see Table 1. Since at zero frequency μ/ε approaches n, the lines on Fig.4 must again converge at frequencies below 0.7 kHz. There is thus a limited frequency region where μ/ε is dependent upon particle size.

Similar work has been carried out at N.O.T.S. by Price and his group[2,10] who varied the ammonium perchlorate particle size in a propellent based upon polybutyl acrylic acid (P.B.A.A.) as the fuel. At a pressure of 200 psi (1379 kN/m^2) it was found that changing the particle size of the oxidizer only changed the steady state burning rate of the propellent.

Consideration of the propellents containing 1% titanium dioxide, I, C and J, Fig.6, shows that the acoustic response has been reduced in each case compared to the propellents containing no titanium dioxide but the most marked effect is shown for propellent I. With all the other propellents used in this work, the acoustic response has been comparatively flat; however, with propellent I it decreases steadily over the whole frequency range, 0.7-4.0 Hz. The acoustic response of propellents C and J both have similar values (~0.6) at high frequencies as observed for propellents containing no titanium dioxide, but they also stay much closer together over the rest of the frequency range. To summarize, 1% titanium dioxide reduces the acoustic response of all the propellents but the effect is greatest when coarse oxidizer has been used and at the high frequencies.

If the maximum pressure-amplitude reached in the T-burner is used as a measure of the stability of burning of the propellent, Fig.7 shows that with no titanium dioxide in the propellent, the propellent containing coarse oxidizer (F) is able to sustain the highest pressure-amplitude of oscillations. However the reverse is true with 1% titanium dioxide present; Fig.8 shows that the propellent containing coarse oxidizer (I) supports the lowest amplitude of pressure oscillations.

The effect of titanium dioxide on each of the propellents containing a different particle size of oxidizer may now be compared:

(i) fine oxidizer: 1% TiO_2 reduces the maximum pressure-amplitude by a factor of approximately 2.5 (Fig.10)

(ii) medium oxidizer: 1% TiO_2 reduces the maximum pressure-amplitude by a factor of approximately 2.5 at high frequencies and by a factor of 10 at low frequencies (Fig.11)

(iii) coarse oxidizer: 1% TiO_2 reduces the maximum pressure-amplitude by a factor of 100-150 over the whole frequency range (Fig.12).

It should be noted that with the propellents containing coarse oxidizer, the maximum pressure-amplitude decreases with increase of frequency whereas with the propellents containing fine oxidizer it increases with increase of frequency.

5.2 Effect of addition of titanium dioxide to the propellent

Four propellents (A,B,C and D) were used for this section of the work containing 4%,2%,1% and 0% of titanium dioxide respectively and a constant 12% USB2. Their burning rates are given in Table 1. Addition of 1% titanium dioxide to propellent D causes an increase in the burning rate of 37% whereas the addition of a further 1% TiO_2 increases the burning rate only up to 45%, i.e. by no more than 8% additional. Increasing the titanium dioxide content from 2 to 4% increases the burning rate by only a further 1%. Thus, under steady state conditions, an addition of 1% titanium dioxide has a marked effect on the burning rate, whilst further additions have only slight effects. The mechanisms by which titanium dioxide influences the steady state burning rate is uncertain at present; however, it is known to have little effect upon the decomposition temperature of ammonium perchlorate[11].

The real parts of the acoustic response, Re (μ/ε), for all three propellents containing titanium dioxide are similar (Fig.14) and significantly less than for the propellent not containing titanium dioxide. Titanium dioxide has, therefore, quite a marked effect on the change in mass burning rate for a given perturbation in pressure and, as in its effect on the steady state combustion, the change is similar for 1%,2% or 4% of titanium dioxide. The actual relative stability of burning under motor conditions, which takes into account the difference in steady state burning rates of the propellents, is shown in Fig.13. It is evident that addition of 1% titanium dioxide is sufficient to promote stability, and that addition of 4% titanium dioxide results in a higher admittance than that for the propellent with 1% titanium dioxide.

Fig.11 shows that all the propellents containing titanium dioxide supported a lower maximum pressure-amplitude in the T-burner than the propellent without titanium dioxide. The propellent containing 4% TiO_2 sustained the lowest pressure-amplitude but the increased effect of 4% as opposed to 1% was most noticeable at the higher frequencies. At the lower frequencies where the reduction in pressure-amplitude was the greatest, the effect was similar regardless of whether 1%,2% or 4% of titanium dioxide had been added to the propellent. A similar trend was evident when the rates of decay of the pressure oscillations in the T-burner were plotted against frequency. These effects are caused by particulate damping of the titanium dioxide in the gas phase.

Summarizing, the above results have shown that titanium dioxide is able to reduce the level to which acoustic pressure oscillations may rise. There is an advantage in using more than 1% titanium dioxide at the higher frequencies (3-4 kHz), but there is nothing to be gained at lower frequencies (1 kHz) by using 4% rather than 1% of titanium dioxide. The acoustic response has also been shown to be lowered by the titanium dioxide, uniformly over the frequency range considered, the reduction being independent of whether 1%, 2% and 4% were added. Since the decay constants for all the propellents (I, C and J) containing 1% titanium dioxide are similar and the acoustic response and maximum pressure-amplitude to which the oscillations build up to are so dependent upon the oxidizer particle size, it follows that titanium dioxide must also exert an effect in the combustion zone. The stabilising effect is greatest when coarse ammonium perchlorate is used as oxidizer.

5.3 Comparison of the experimentally determined response function with that calculated by the McClure theory

Figs.4 and 9 show the response functions for propellents D, E and F as found experimentally and calculated theoretically[8]. Since the variables had been reduced to a minimum (variation in only the ammonium perchlorate particle size), one might have expected theory to predict the trend correctly. As may be seen from Figs.4 and 5, the two are at variance, both in shape of the curves and in relative order.

A further test was made to compare McClure's[4] theory using propellents A,B,C and D in which the only variable was the amount of titanium dioxide. Figs.14 and 15 show respectively the real part of the response function as found experimentally and calculated from McClure's theory. There is an element

of agreement, in that both show propellent D to have the highest response function in the frequency range covered experimentally. Apart from this, however, there are no obvious correlations.

It must be accepted that even with these model propellents, theory has failed to predict the trends found in the experimental results.

5.4 Effect of variation of the oxidizer/fuel ratio of the propellent

The effect on the acoustic response of varying the ammonium perchlorate/USB2 ratio is shown in Fig.17. The change in oxidizer/fuel ratio was from 6.1 to 9.5 (stoichiometric is at 9.81) but the change in acoustic response was slight. Propellent M which is close to the stoichiometric mixture does have a marginally higher acoustic response, but propellents D,L and M are all similar. Propellent N, which is the most fuel-rich, shows a more definite trend to exhibit the lowest acoustic response, at the higher frequencies. Fig.20 shows the probable explanation for this, in that the energy content for propellent N is considerably lower than for the other propellents. The flame temperature and specific impulse were calculated theoretically for propellent compositions D,L,M and N for motor pressures of 1000 psi (6895 kN/m^2) and expansion to 14.7 psi (101.3 kN/m^2) and are shown in Fig.20.

Fig.18, which illustrates the maximum pressure-amplitude reached in the T-burner firings, shows a similar finding, in that the propellents are all able to support approximately similar pressure-amplitudes. However, if the pressure-amplitude is estimated for each propellent at specific frequencies (1.5, 2.5 and 4.0 kHz) and plotted against oxidizer/fuel ratio, Fig.19 suggests that the maximum pressure-amplitude at each frequency is proportional to the oxidizer/fuel ratio. As the propellent becomes more fuel-rich so the frequency corresponding to the maximum pressure-amplitude is increased.

The change in linear burning rate of the propellent as the ratio of ammonium perchlorate to USB2 is varied is given in Table 1. As expected the almost stoichiometric propellent, M, has a faster burning rate than the more fuel-rich propellents.

Rice[3], who has carried out similar experiments on an ammonium perchlorate/P.B.A.A. propellent system, found that the propellent most fuel-rich had the highest acoustic response and vice versa. This is in direct contradiction to the results found here. The most likely cause for the different findings is that Rice's experiments were carried out at a mean pressure of 200 psi (1379 kN/m^2), whereas the present firings were all at 1000 psi (6895 kN/m^2)

and a different flame sturcture was probably present. These results illustrate the importance of determining the acoustic response of the propellents at pressures representative of motor firings.

6 CONCLUSIONS

(1) The stability of burning of a solid propellent can be affected by a change in the ammonium perchlorate particle size:

(i) In the absence of titanium dioxide, at high frequencies (4 kHz) the acoustic response is independent of ammonium perchlorate particle size, but at the lower frequencies (1 kHz) the coarse oxidizer produces the least stable propellent.

(ii) In the presence of 1% titanium dioxide, the acoustic response is lowered for each propellent containing a different oxidizer particle size but the effect is greatest for the coarse oxidizer at the higher frequencies.

(2) Titanium dioxide promotes stable burning in plastic propellents by two major routes:

(i) In the gas phase it promotes acoustic damping by means of the fine suspended solid particulate matter. The amount of gas phase particle damping is proportional to the percentage of titanium dioxide added to the propellent. The proportionality is most noticeable at the high frequencies (4.0 kHz) whereas the effectiveness of the damping is most evident at lower frequencies (1.5 kHz).

(ii) Titanium dioxide also exerts an influence on the combustion zone and additions of 1%, 2% or 4% titanium dioxide to the standard medium grade oxidizer propellent all lower the acoustic response by a similar amount, approximately 50%, over the whole frequency range. However, 1% titanium dioxide exerts a far greater stabilising influence on the combustion of the propellent containing coarse oxidizer at higher frequencies.

(3) The experimental results for simple propellent systems containing a minimum number of variables do not endorse the theory proposed by McClure.

(4) The variation of the oxidizer/fuel ratio over a comparatively large range has little effect on the stability of burning of plastic propellents. The results show that as the energy level of the propellent is reduced so is its tendency to instability, but the effect is small. This finding is in direct contradiction to some earlier results elsewhere but a probable explanation has been suggested.

Acknowledgment

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Table 1

COMPOSITIONS AND SOME BALLISTIC PROPERTIES OF PROPELLENTS A → J

Propellent		Ammonium perchlorate, %	Specific surface area of ammonium perchlorate, So	USB2* %	TiO_2 %	Linear burning rate r, at 1000 psig (6895 kN/m^2)	Pressure exponent n
E 4156/T1	A	84	1930 cm^{-1}	12	4	26.0 mm/sec	0.70
E 3620/T2	B	86	1930 cm^{-1}	12	2	25.8 mm/sec	0.50
E 3867/T5	C	87	1930 cm^{-1}	12	1	23.9 mm/sec	0.49
E 3533/T6	D	88	1930 cm^{-1}	12	0	17.4 mm/sec	0.59
E 3533/T5	E	88	9100 cm^{-1}	12	0	27.3 mm/sec	0.58
E 3533/T4	F	88	400 cm^{-1}	12	0	14.2 mm/sec	0.49
E 3867/T7	I	87	400 cm^{-1}	12	1	18.3 mm/sec	-
E 3867/T6	J	87	9100 cm^{-1}	12	1	32.5 mm/sec	-

*USB2 consists of 90% polyisobutene ($(CH_2)_n$)

and 10% S101 ($C_{1.0}H_{1.873}O_{0.173}$)

Table 2

COMPOSITIONS AND SOME BALLISTIC PROPERTIES OF PROPELLENTS N, D, L and M

Propellent		Ammonium perchlorate, %	Specific surface area of ammonium perchlorate, So	USB2, %	TiO_2 %	Linear burning rate r, at 1000 psig (6895 kN/m^2)	Flame temperature	Specific impulse 1000 psi (6845 kN/m^2) → 14.7 psi, lbf sec/lbm	Ratio oxidizer/ USB2
E 4166/T1	N	86	1930 cm^{-1}	14	0	16.1 mm/sec	2759 ^oK	243.0	6.14
E 3533/T6	D	88	1930 cm^{-1}	12	0	17.4 mm/sec	2936 ^oK	248.3	7.33
E 3102/T1	L	89.5	1930 cm^{-1}	10.5	0	20.8 mm/sec	3004 ^oK	251.3	8.52
E 4018/S8	M	90.5	1930 cm^{-1}	9.5	0	22.4 mm/sec	3000 ^oK	252.0	9.53
-	-	90.75*	-	9.25	0	-	2992 ^oK	251.6	9.81

*This propellent contains the theoretical stoichiometric ratio

Table 3

ADDITIONAL VALUES USED FOR THEORETICAL CALCULATION OF THE RESPONSE FUNCTION

Body temperature of propellent	T_c	$= 293^{\circ}K$
Surface temperature of solid	T_o	$= 660^{\circ}K$
Ignition temperature	T_I	$= 2100^{\circ}K$
Thermal conductivity of solid	λ_s	$= 5 \times 10^{-4}$ cal sec^{-1} cm^{-1} $^{\circ}K^{-1}$
Thermal conductivity of gas	λ	$= 5 \times 10^{-4}$ cal sec^{-1} cm^{-1} $^{\circ}K^{-1}$
Specific heat of solid	C_s	= Specific heat of gas at const. pressure, $C_p = 0.333$ cal gm^{-1} $^{\circ}K^{-1}$
Density of solid	ρ_s	$= 1.705$ gm cm^{-3}
Enthalpy of solid phase reaction	h_v	$= 200$ cal gm^{-1}
Molecular weight of gaseous products	M	$= 24.3$
Ratio of specific heats for the gaseous products	Cp/Cv	$= 1.22$
Sensitivity of mass burning rate to temperature gradient of solid surface	α	$= -1$
Activation energy	A_s	$= 50000$ cal mole^{-1}

NOMENCLATURE

c	velocity of sound
f	frequency
L	length of burner tube
M	molecular weight
$\bar{m}$	mass burning rate of solid propellent
n	pressure exponent
$\bar{P}$	mean pressure
P_A	acoustic pressure amplitude
r	linear burning rate
T_f	flame temperature
$\bar{v}$	mean velocity of product gases at the burning surface
Y	specific acoustic admittance
α_g	logarithmic rate of growth of pressure oscillations
α_d	logarithmic rate of decay of pressure oscillations
λ	ratio of specific heats Cp/Cv
ε	fractional perturbation of pressure
ρ_{gas}	density of product gases
ρ_{solid}	density of solid propellent
μ	fractional perturbation of mass flow rate associated with ε

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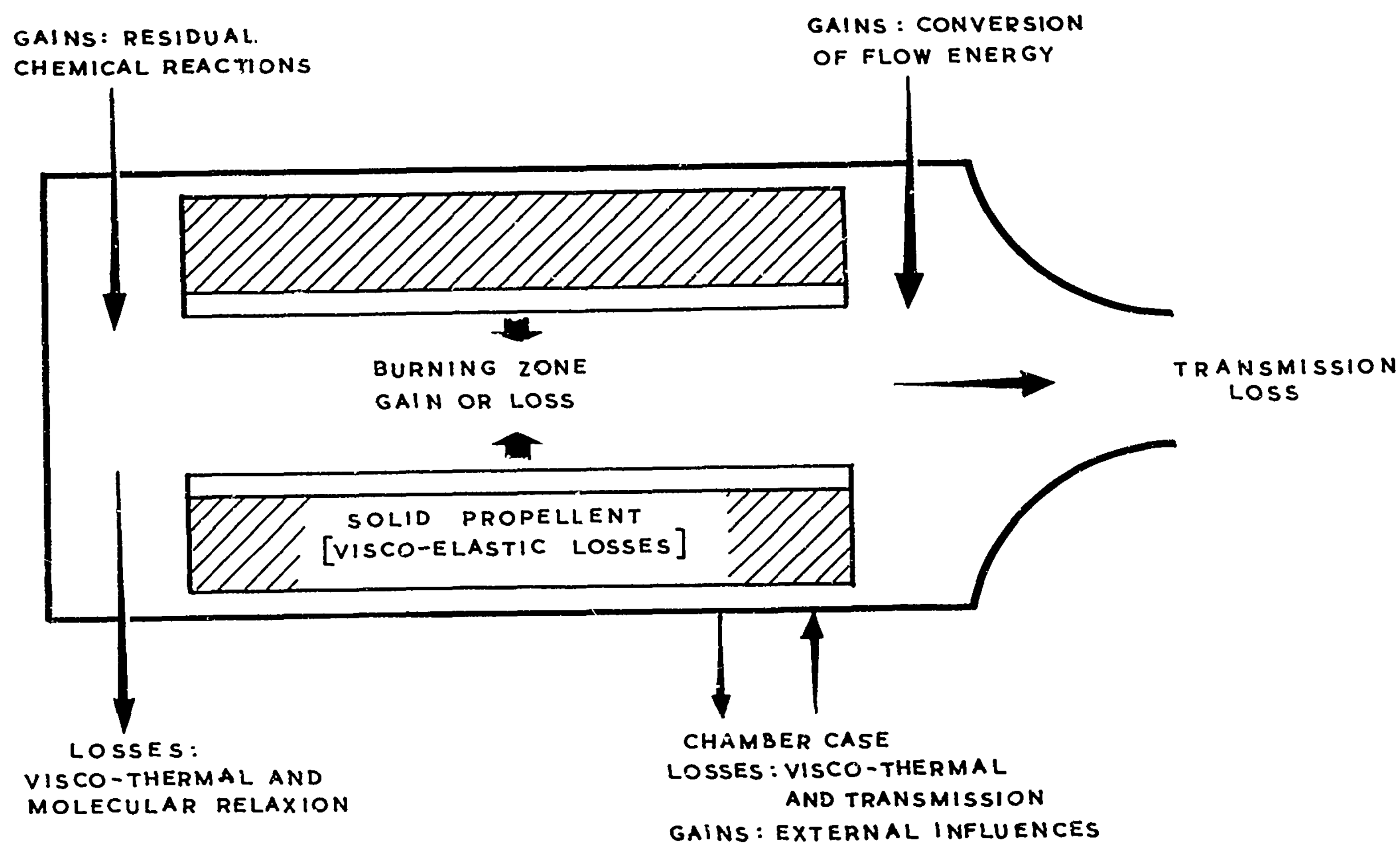


FIG. 1 DIAGRAM OF ROCKET MOTOR SHOWING MAIN SOURCES OF ACOUSTIC GAINS AND LOSSES

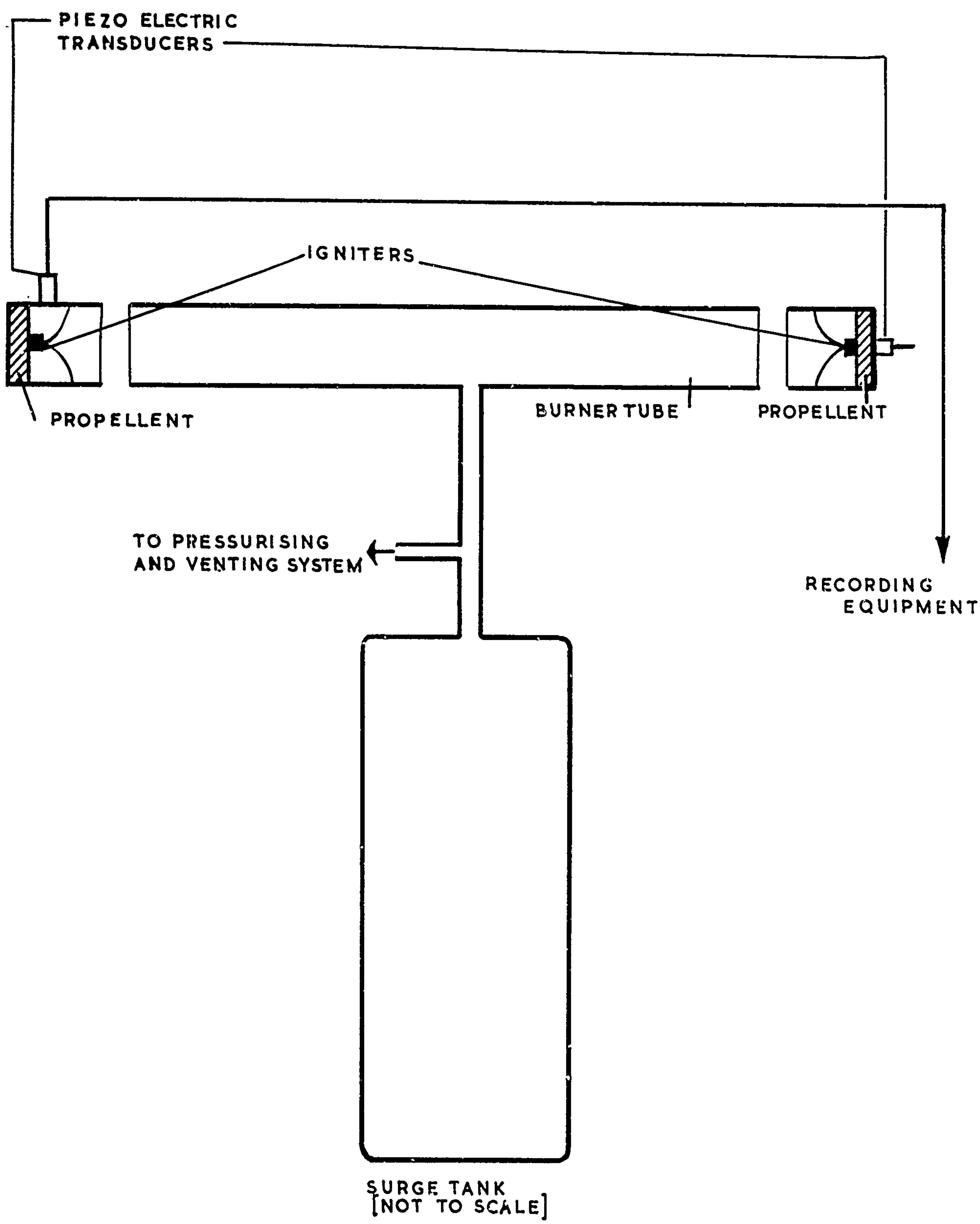
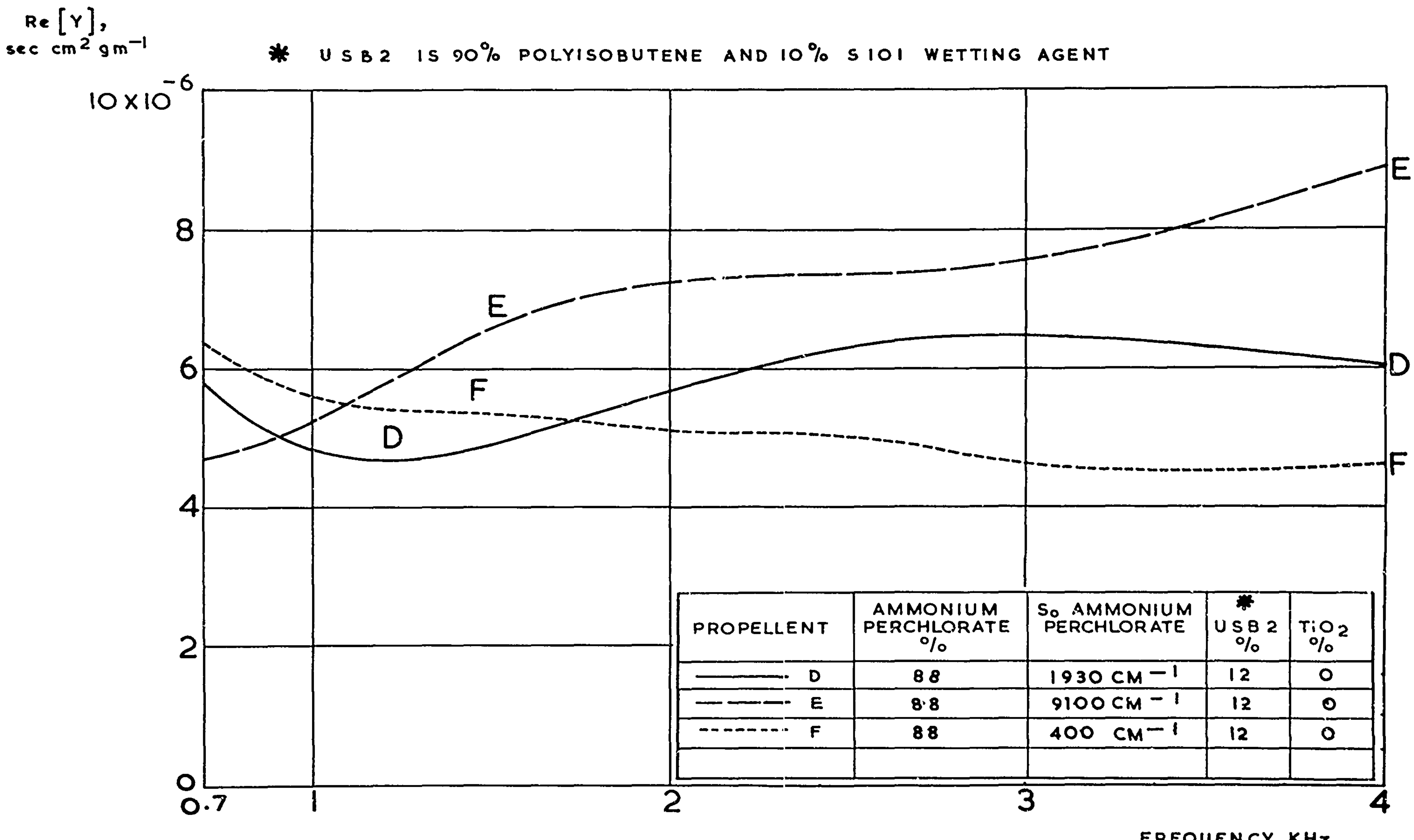


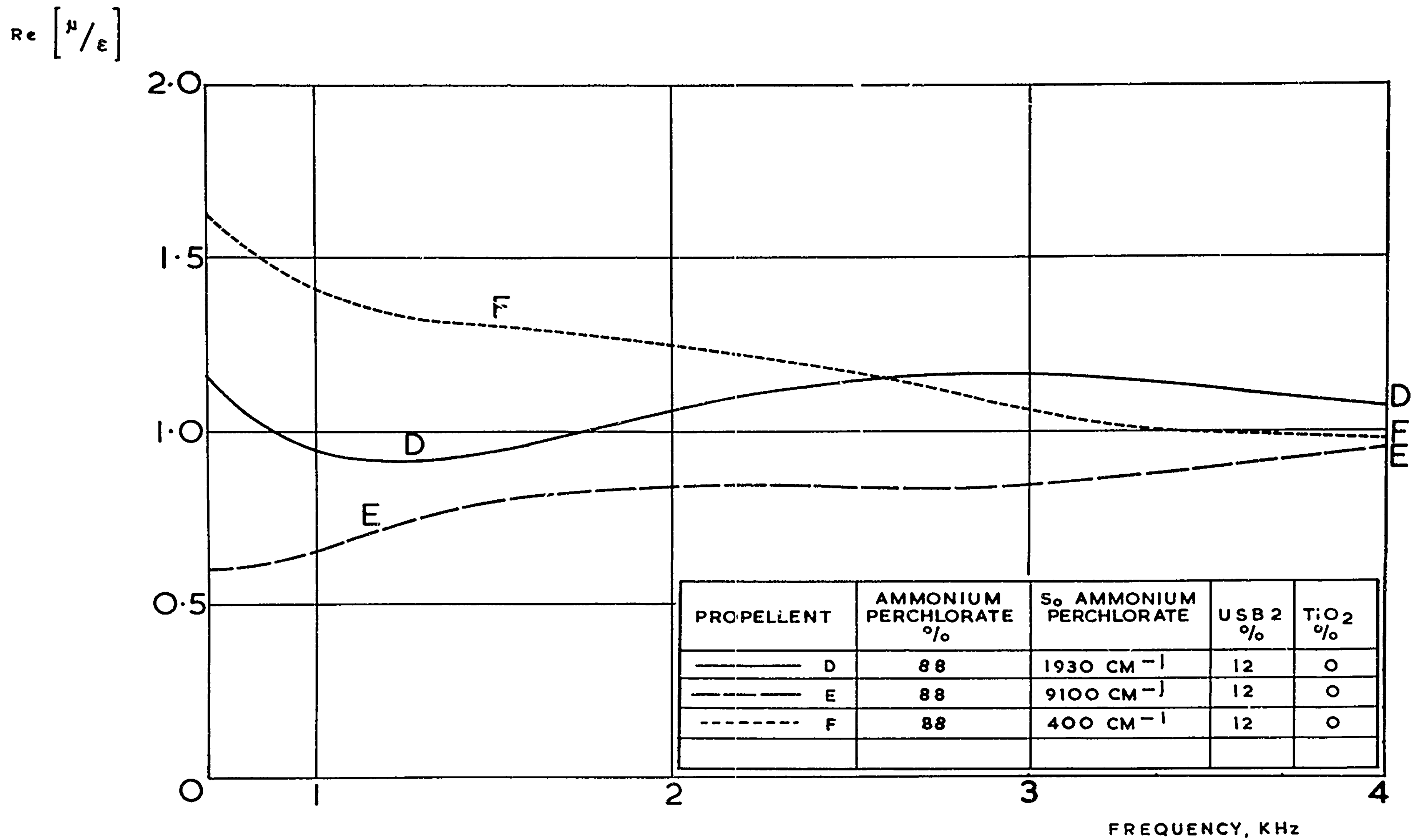
FIG. 2 DIAGRAM OF 'T' BURNER



PROPELLENT	AMMONIUM PERCHLORATE %	S_o AMMONIUM PERCHLORATE	* USB 2 %	TiO_2 %
——— D	88	1930 CM^{-1}	12	0
— — — E	8·8	9100 CM^{-1}	12	0
- - - - - F	88	400 CM^{-1}	12	0

* USB2 IS 90% POLYISOBUTENE AND 10% S101 WETTING AGENT

FIG.3 EFFECT OF OXIDISER PARTICLE SIZE ON Re[Y] FOR PROPELLENTS CONTAINING 0% TiO_2 [PROPELLENTS F,D,E]



PROPELLENT	AMMONIUM PERCHLORATE %	S_o AMMONIUM PERCHLORATE	USB 2 %	TiO_2 %
——— D	88	1930 CM^{-1}	12	0
— — — E	88	9100 CM^{-1}	12	0
- - - - - F	88	400 CM^{-1}	12	0

FIG. 4 EFFECT OF OXIDISER PARTICLE SIZE ON Re [μ/ε] FOR PROPELLENTS CONTAINING 0% TiO_2 [PROPELLENTS F,D,E]

PROPELLENT	AMMONIUM PERCHLORATE %	S_o AMMONIUM PERCHLORATE	USB 2 %	TiO_2 %
----------- I	87	400 CM^{-1}	12	1
———— C	87	1930 CM^{-1}	12	1
— — — J	87	9100 CM^{-1}	12	1

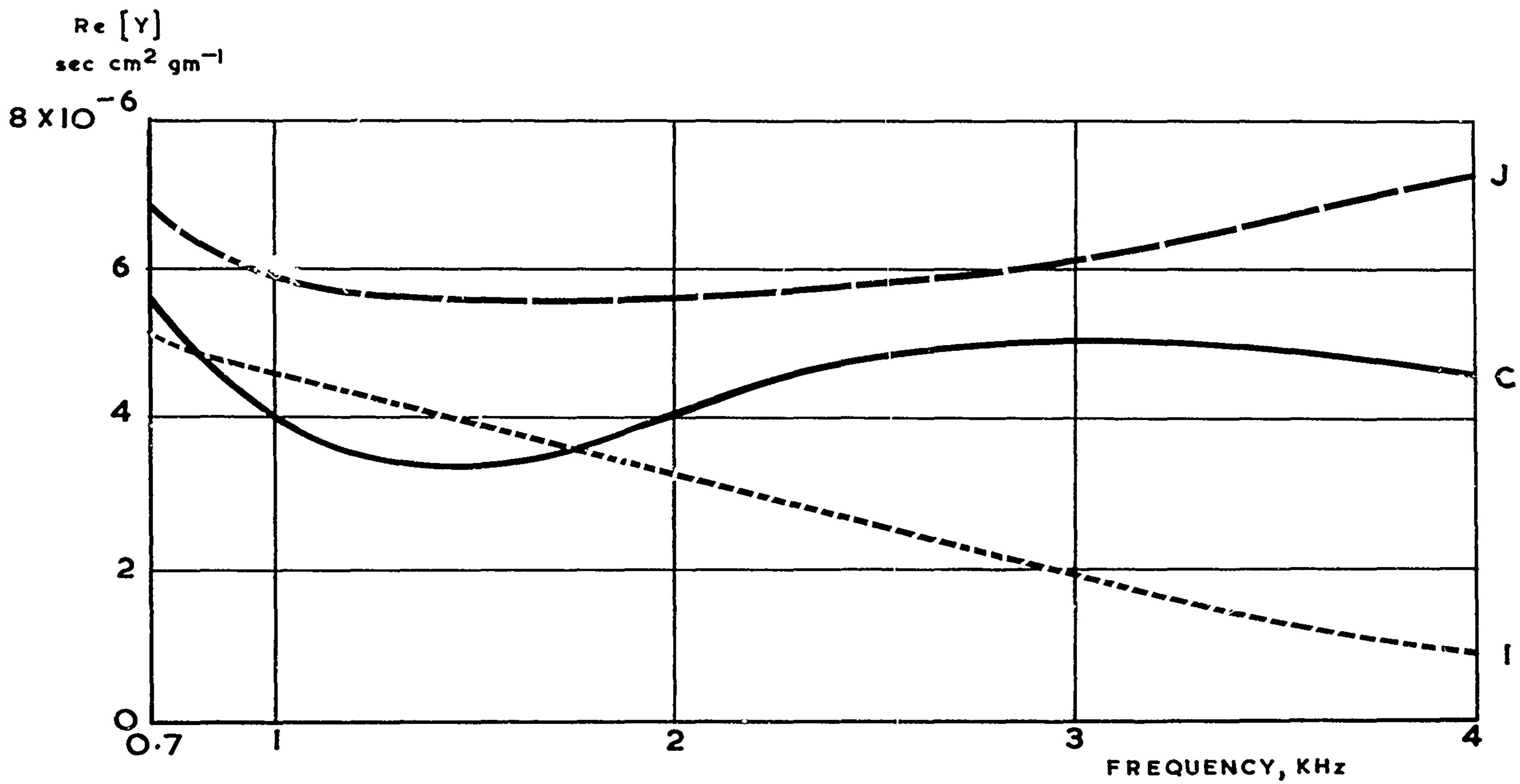


FIG. 5 EFFECT OF OXIDISER PARTICLE SIZE ON Re[Y] FOR PROPELLENTS CONTAINING 1% TiO_2 [PROPELLENTS I, C, J]

PROPELLENT	AMMONIUM PERCHLORATE %	So AMMONIUM PERCHLORATE	USB 2 %	TiO2 %
-------- I	87	400 CM^{-1}	12	1
——— C	87	1930 CM^{-1}	12	1
— — — J	87	9100 CM^{-1}	12	1

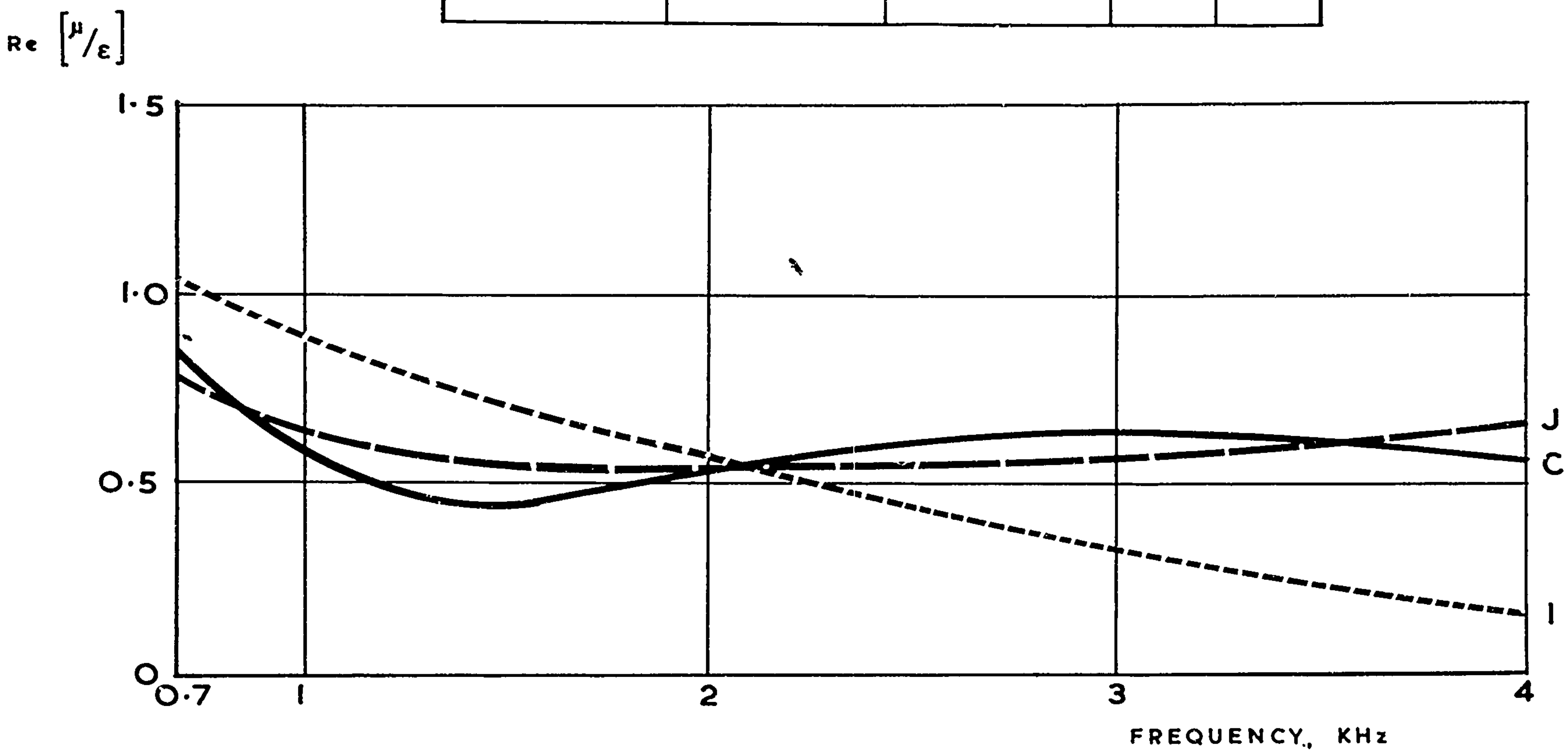
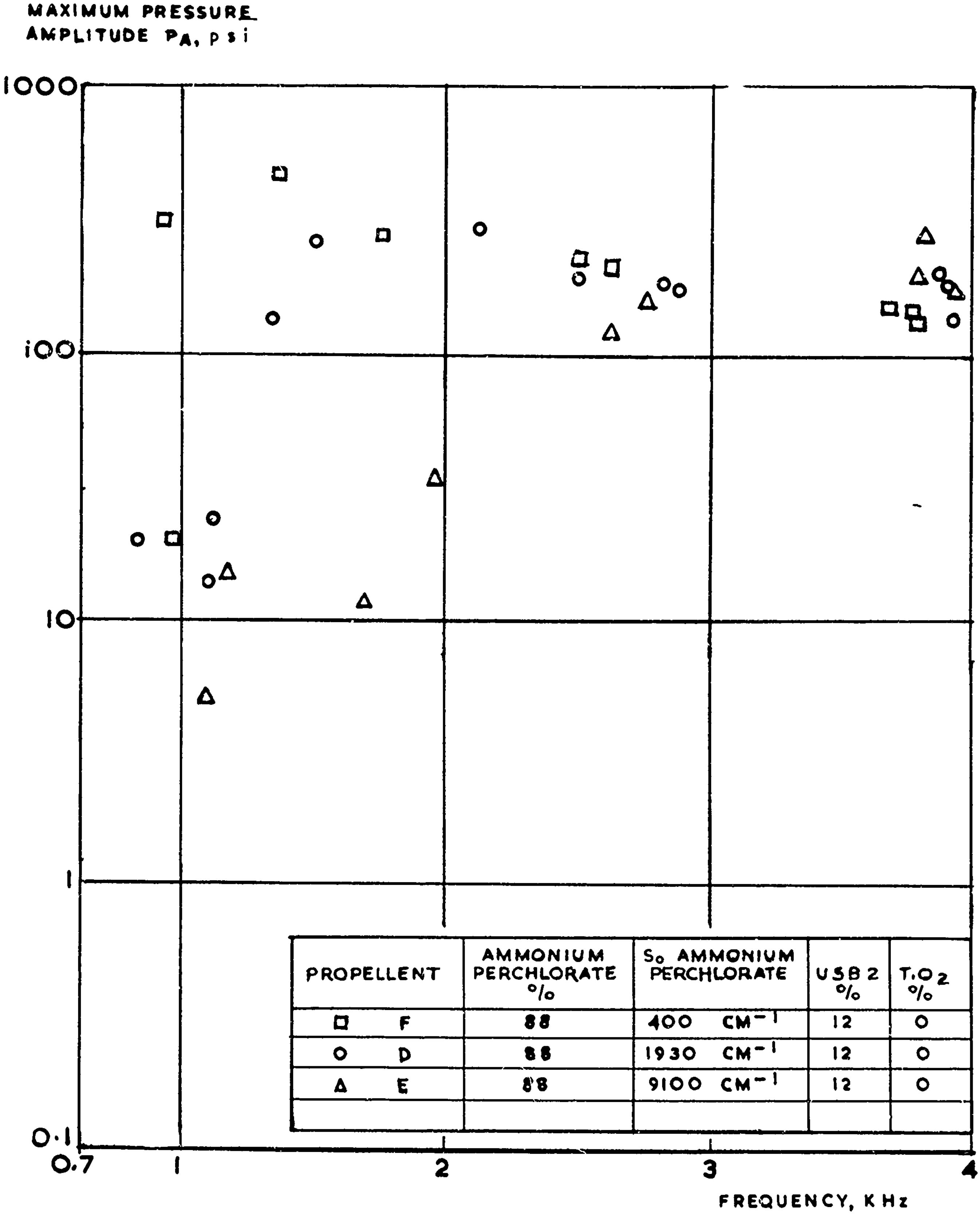
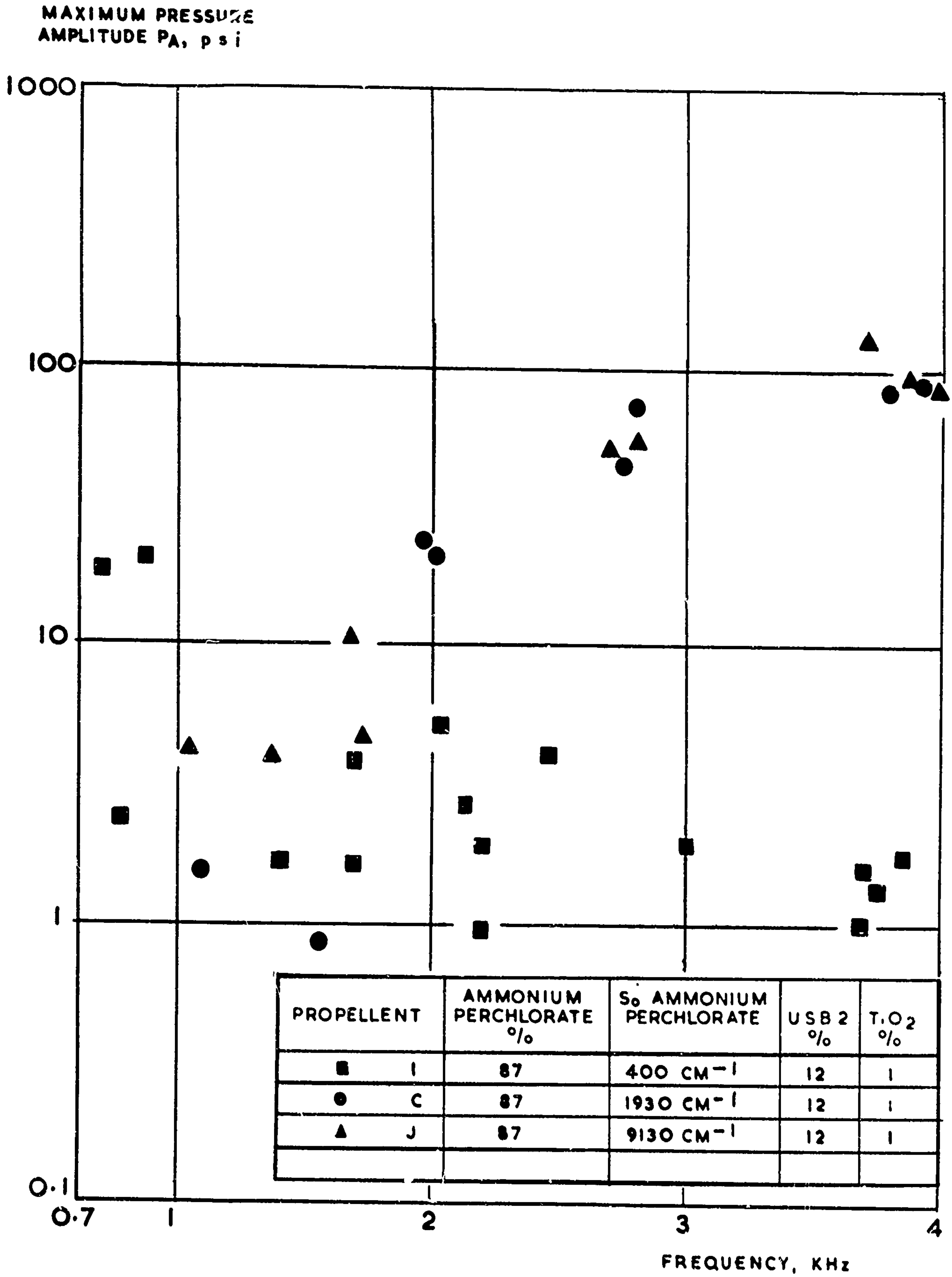


FIG. 6 EFFECT OF OXIDISER PARTICLE SIZE ON Re $[\mu/\varepsilon]$ FOR PROPELLENTS CONTAINING 1% TiO_2 [PROPELLENTS I, C, J]



PROPELLENT		AMMONIUM PERCHLORATE %	So AMMONIUM PERCHLORATE	USB 2 %	T.O 2 %
□	F	88	400 CM^{-1}	12	0
○	D	88	1930 CM^{-1}	12	0
△	E	88	9100 CM^{-1}	12	0

FIG.7 EFFECT OF OXIDISER PARTICLE SIZE ON MAXIMUM PRESSURE-AMPLITUDE REACHED IN T BURNER FOR PROPELLENTS CONTAINING 0% TiO_2 [PROPELLENTS F,D,E]



PROPELLENT		AMMONIUM PERCHLORATE %	S_0 AMMONIUM PERCHLORATE	USB 2 %	TiO_2 %
■	I	87	400 CM^{-1}	12	1
●	C	87	1930 CM^{-1}	12	1
▲	J	87	9130 CM^{-1}	12	1

FIG. 8 EFFECT OF OXIDISER PARTICLE SIZE ON MAXIMUM PRESSURE AMPLITUDE REACHED IN T- BURNER FOR PROPELLENTS CONTAINING 1% TiO_2

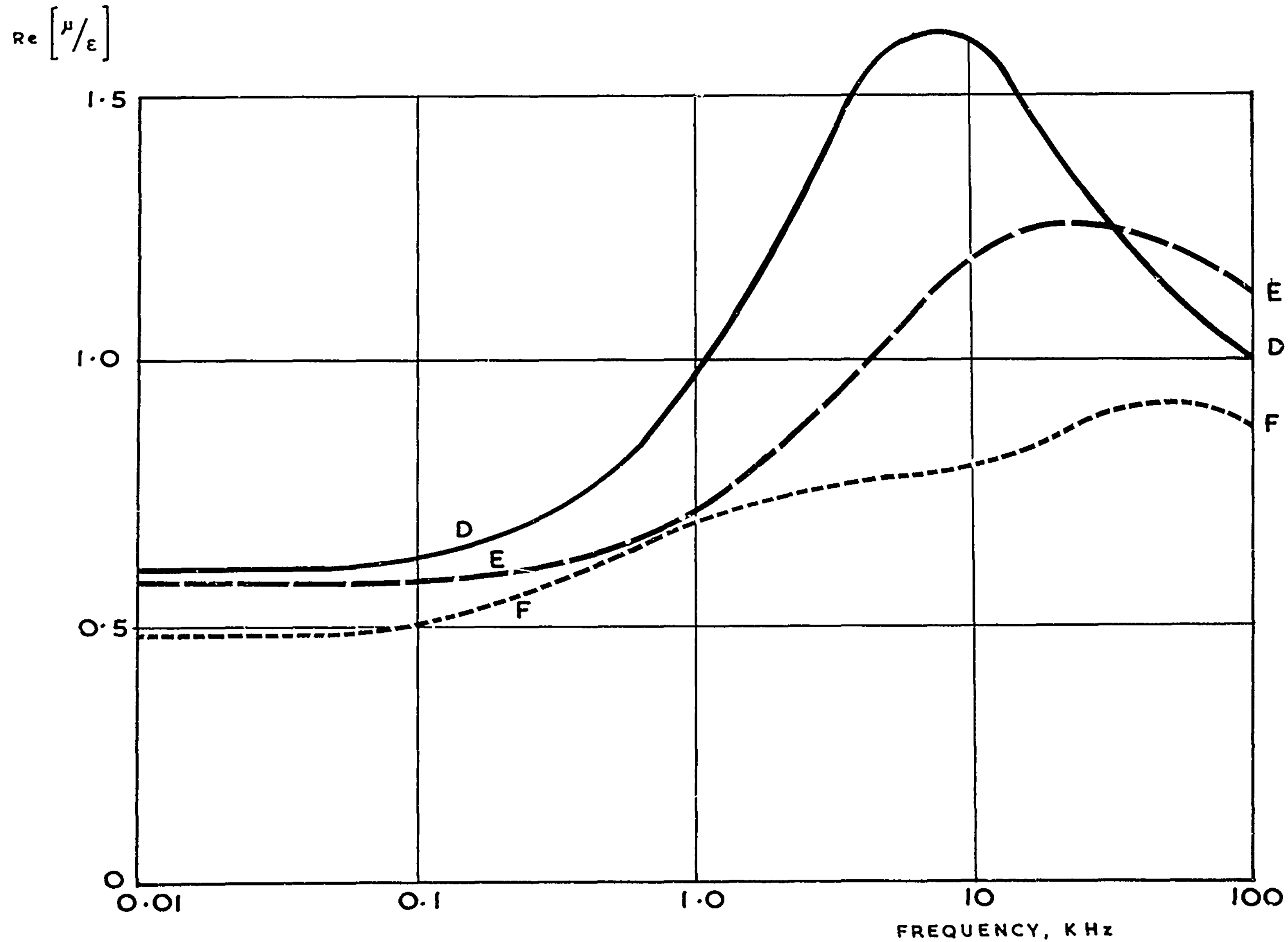
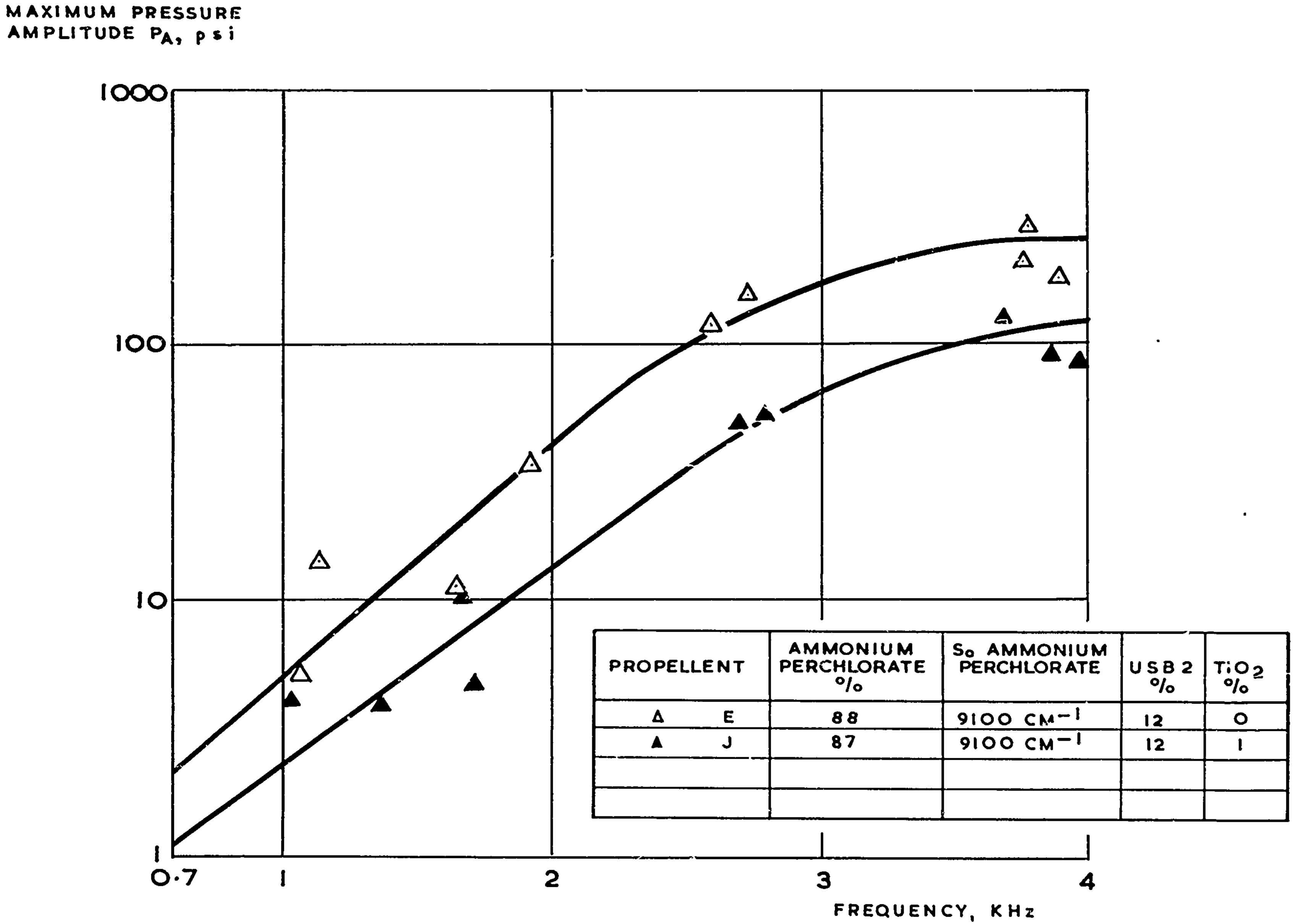


FIG. 9 Re$\left[\mu/\varepsilon\right]$ AS PREDICTED BY M^C CLURE THEORY, FOR PROPELLENTS F, D, E



PROPELLENT		AMMONIUM PERCHLORATE %	S_o AMMONIUM PERCHLORATE	USB 2 %	TiO_2 %
△	E	88	9100 CM^{-1}	12	0
▲	J	87	9100 CM^{-1}	12	1

FIG. 10 EFFECT OF 1% TiO_2 IN PROPELLENT WITH FINE OXIDISER ON MAXIMUM PRESSURE AMPLITUDE [PROPELLENTS E, J]

PROPELLENT		AMMONIUM PERCHLORATE %	S_o AMMONIUM PERCHLORATE	USB 2 %	TiO_2 %
○	D	88	1930 CM^{-1}	12	0
●	C	87	1930 CM^{-1}	12	1
◐	B	86	1930 CM^{-1}	12	2
◑	A	84	1930 CM^{-1}	12	4

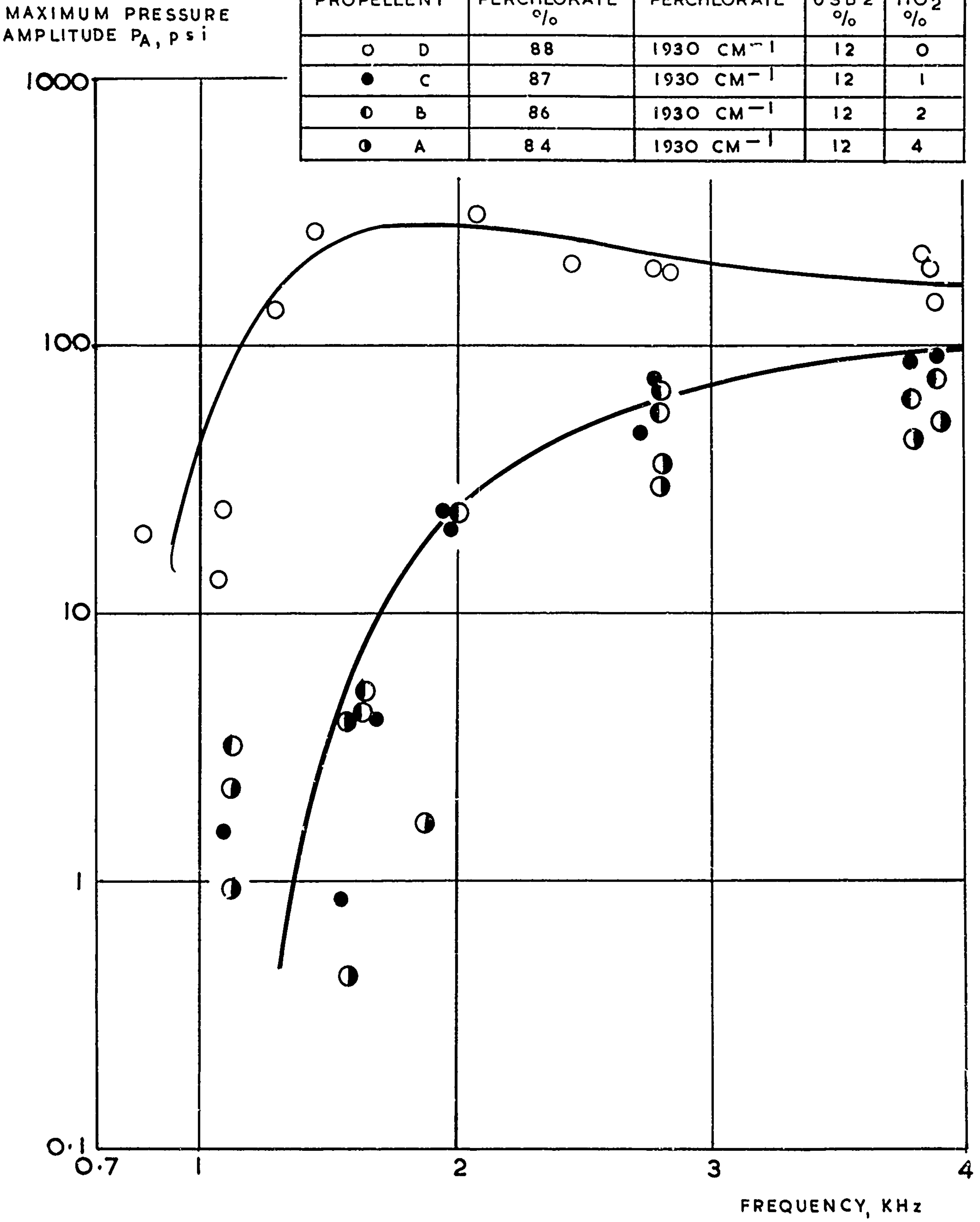
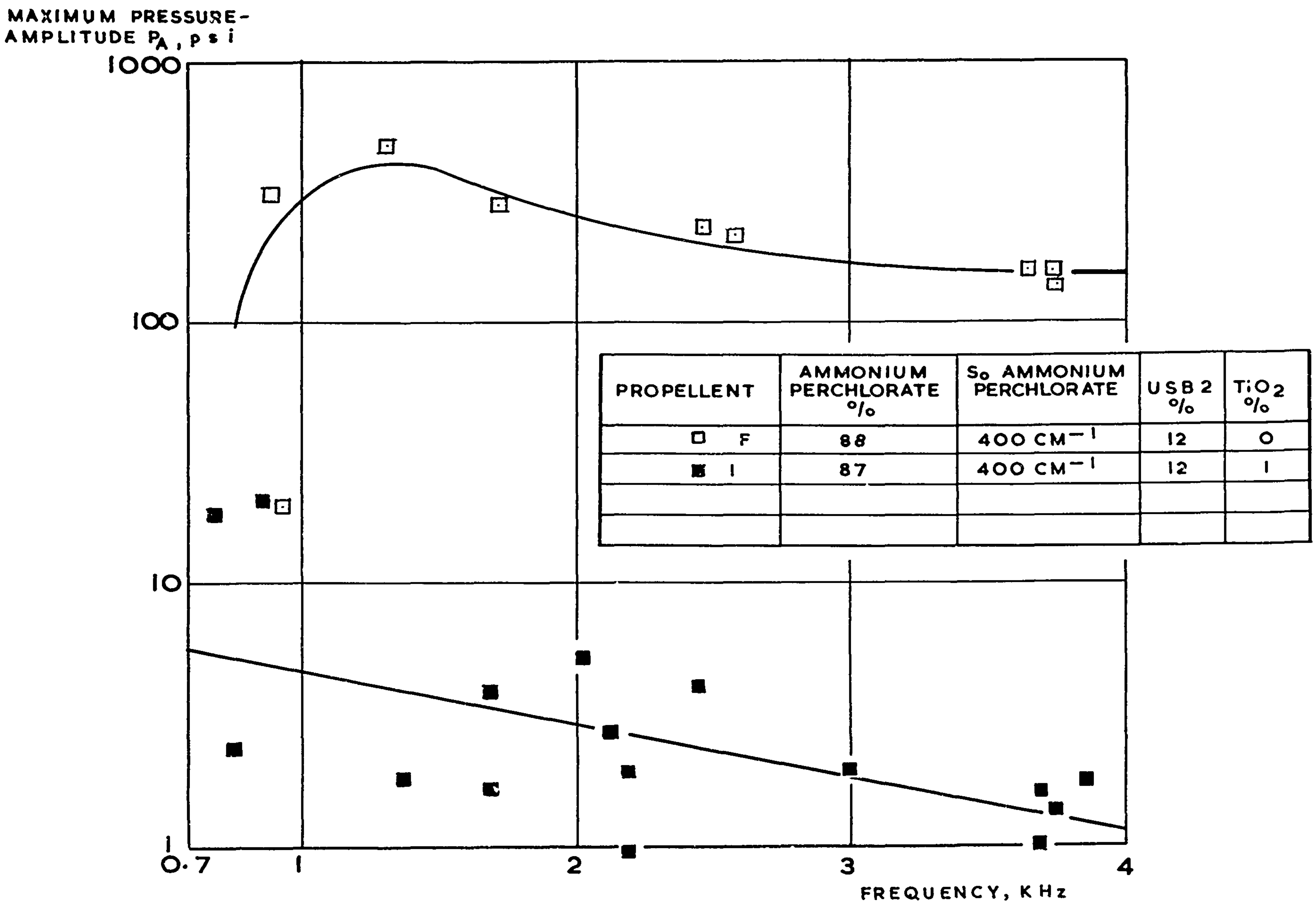
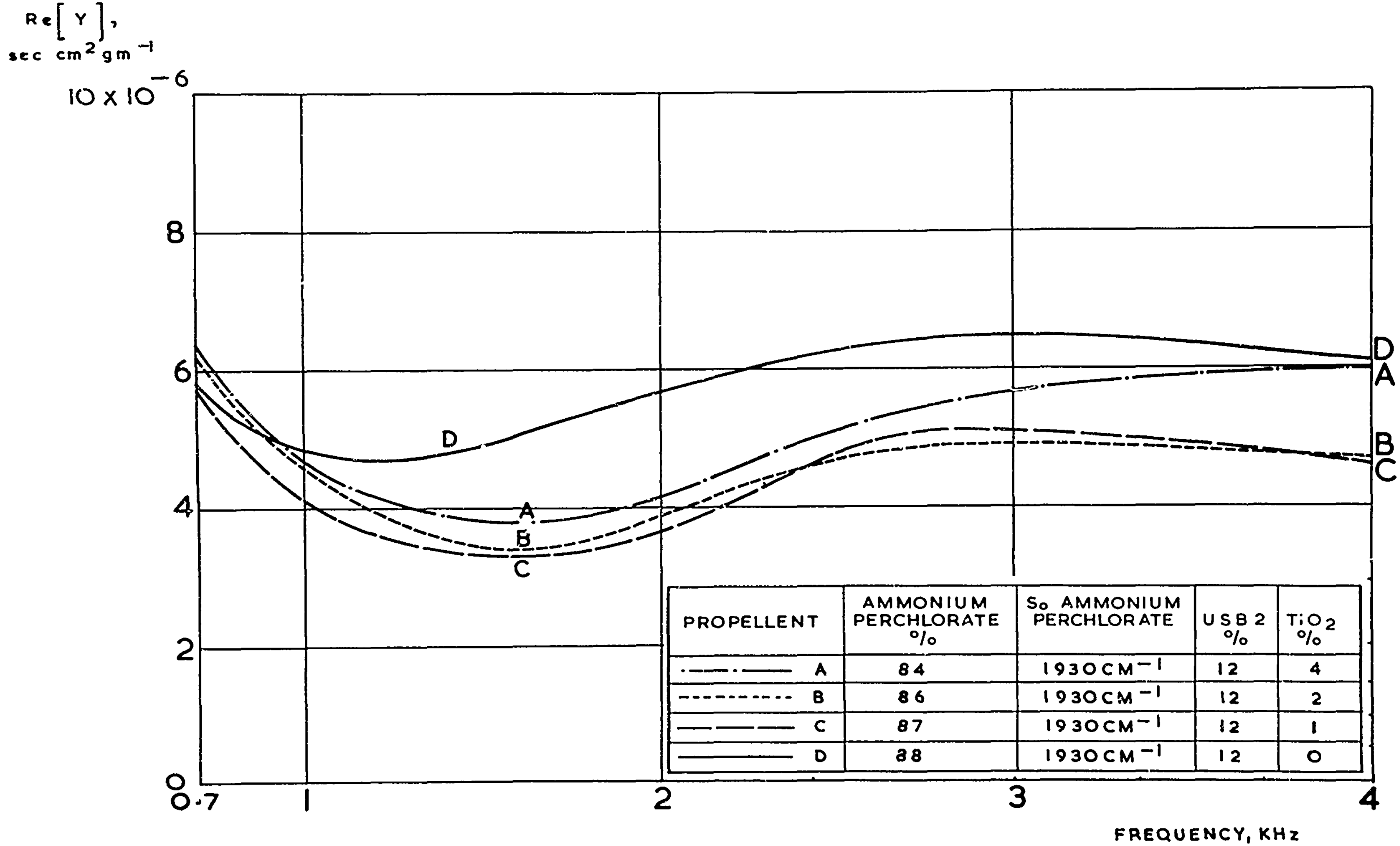


FIG. 11 EFFECT OF 1%, 2%, 4% TiO_2 IN PROPELLENT WITH MEDIUM GRADE OXIDISER ON MAXIMUM PRESSURE-AMPLITUDE [PROPELLENTS D, C, B, A]



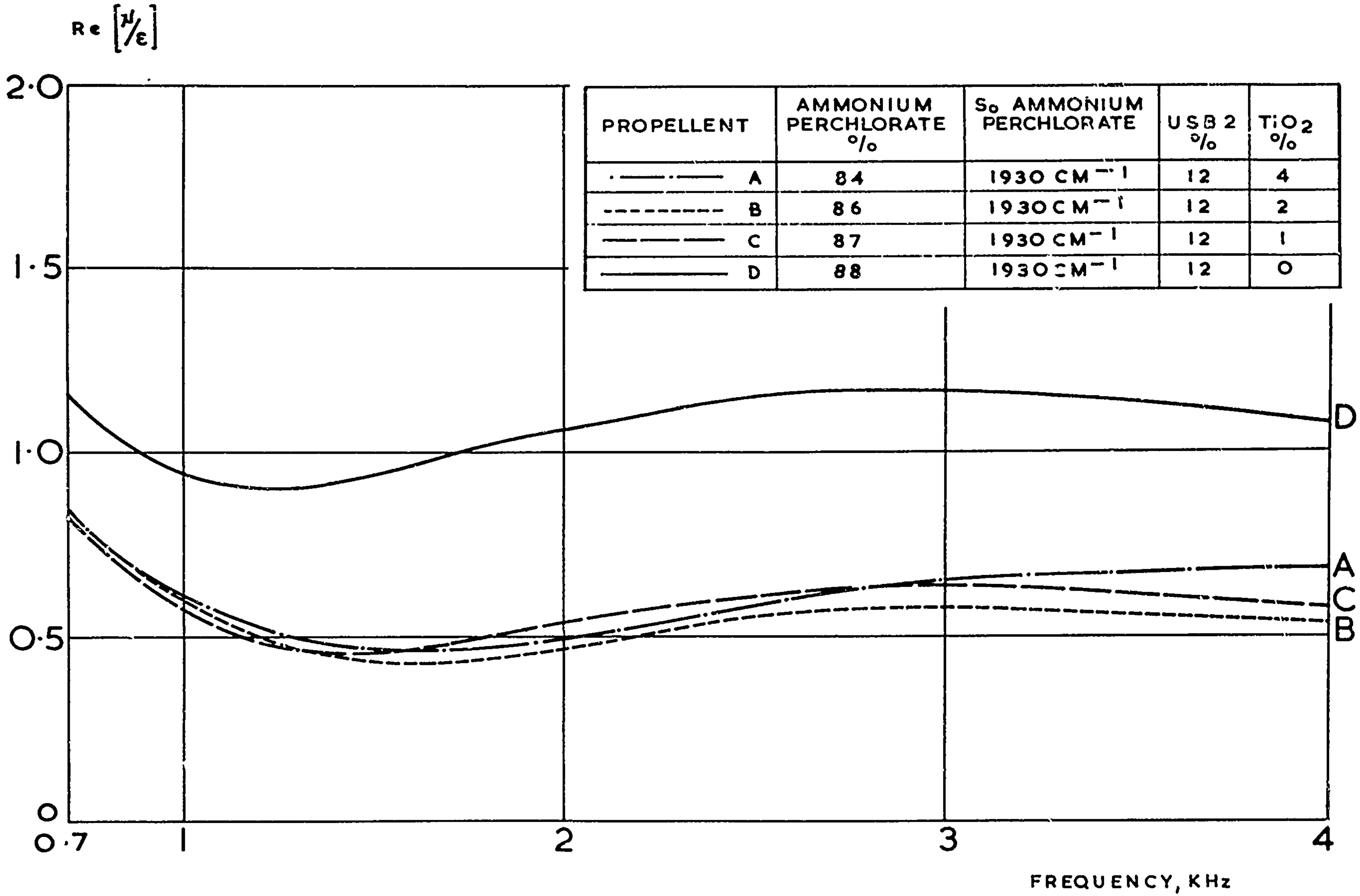
PROPELLENT	AMMONIUM PERCHLORATE %	S_o AMMONIUM PERCHLORATE	USB 2 %	TiO_2 %
□ F	88	400 CM^{-1}	12	0
■ I	87	400 CM^{-1}	12	1

FIG. 12 EFFECT OF 1% TiO_2 IN PROPELLENT WITH COARSE OXIDISER ON MAXIMUM PRESSURE-AMPLITUDE [PROPELLENTS F, I]



PROPELLENT	AMMONIUM PERCHLORATE %	S_o AMMONIUM PERCHLORATE	USB 2 %	TiO_2 %
A (-·-·-)	84	$1930 CM^{-1}$	12	4
B (-------)	86	$1930 CM^{-1}$	12	2
C (— — —)	87	$1930 CM^{-1}$	12	1
D (———)	88	$1930 CM^{-1}$	12	0

FIG. 13 EFFECT OF CONCENTRATION OF TiO_2 ON Re[Y] [PROPELLENTS D,C,B,A]



PROPELLENT	AMMONIUM PERCHLORATE %	S_o AMMONIUM PERCHLORATE	USB 2 %	TiO_2 %
A	84	1930 CM^{-1}	12	4
B	86	1930 CM^{-1}	12	2
C	87	1930 CM^{-1}	12	1
D	88	1930 CM^{-1}	12	0

FIG. 14 EFFECT OF CONCENTRATION OF TiO_2 ON Re $[\mu/\varepsilon]$ [PROPELLENTS D,C,B,A]

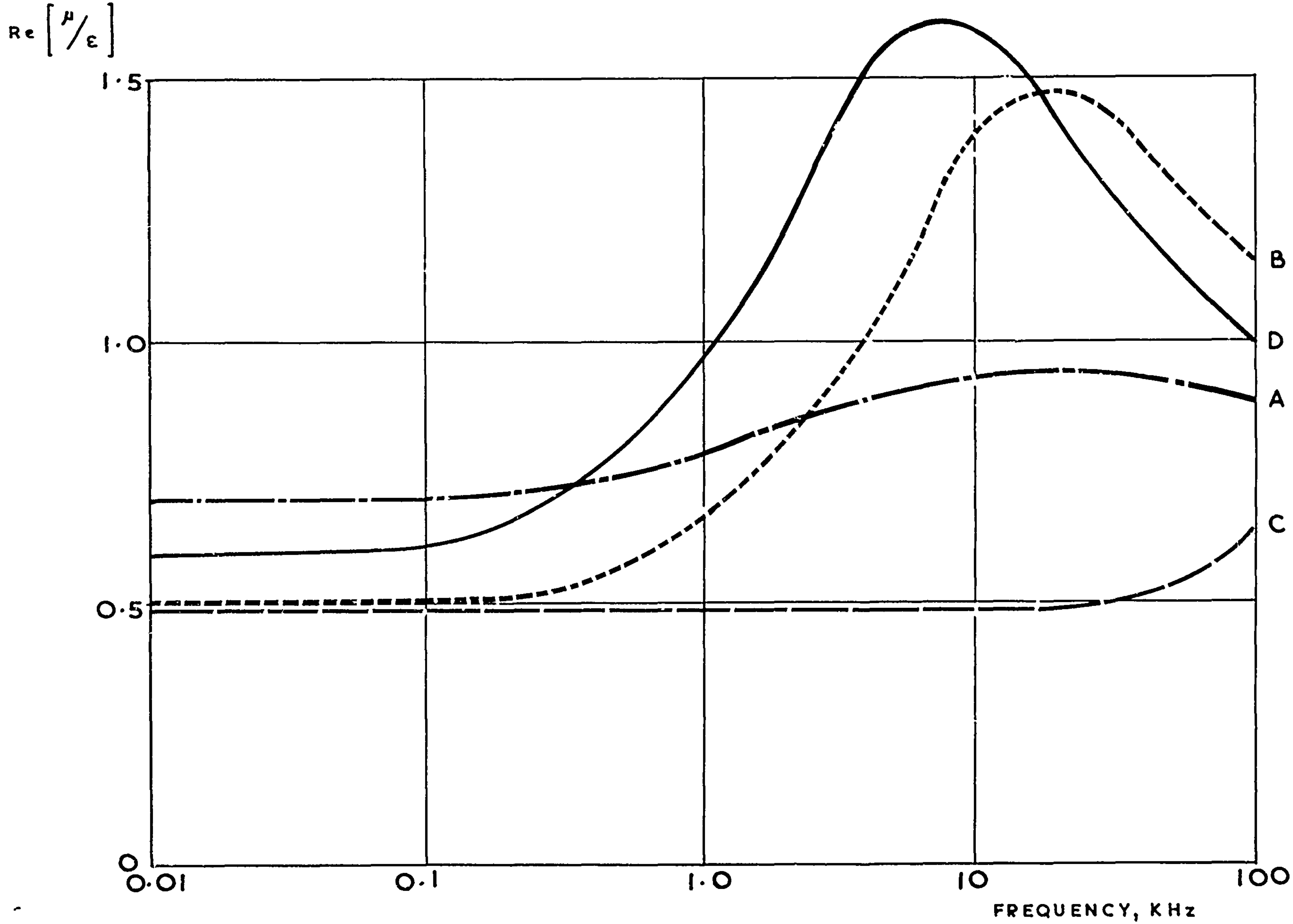


FIG. 15 Re $\left[\mu/\varepsilon\right]$ AS PREDICTED BY McCLURE THEORY FOR PROPELLENTS D,C,B,A

PROPELLENT	AMMONIUM PERCHLORATE %	S_o AMMONIUM PERCHLORATE	USB 2 %	TiO_2 %
N	86	1930 CM^{-1}	14	0
D	88	1930 CM^{-1}	12	0
L	89·5	1930 CM^{-1}	10·5	0
M	90·5	1930 CM^{-1}	9·5	0

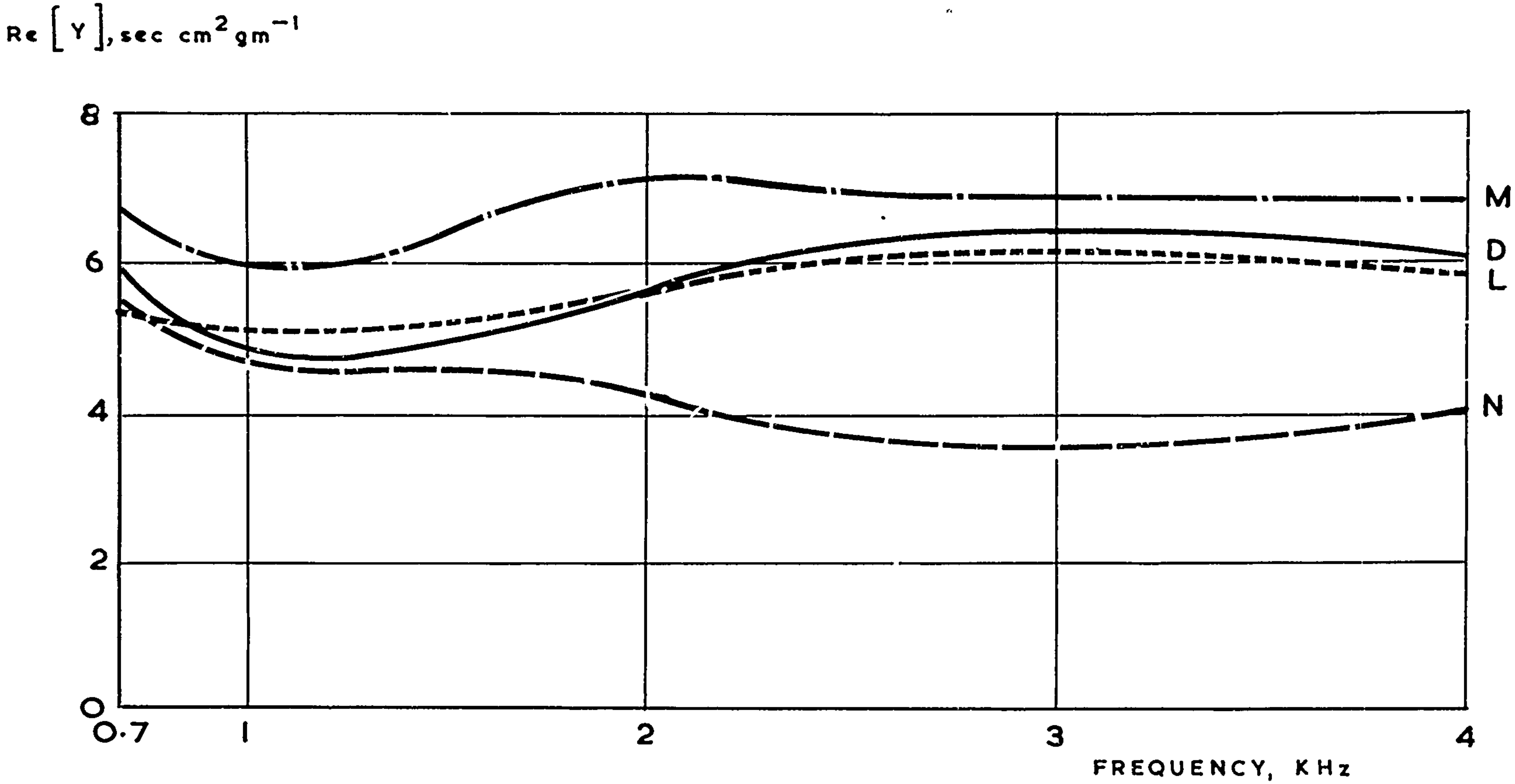


FIG. 16 EFFECT OF VARYING THE OXIDISER/FUEL RATIO ON Re [Y] [PROPELLENTS N, D, L, M]

PROPELLENT	AMMONIUM PERCHLORATE %	So AMMONIUM PERCHLORATE	USB 2 %	TiO_2 %
N	86	1930 CM^{-1}	14	0
D	88	1930 CM^{-1}	12	0
L	89·5	1930 CM^{-1}	10·5	0
M	90·5	1930 CM^{-1}	9·5	0

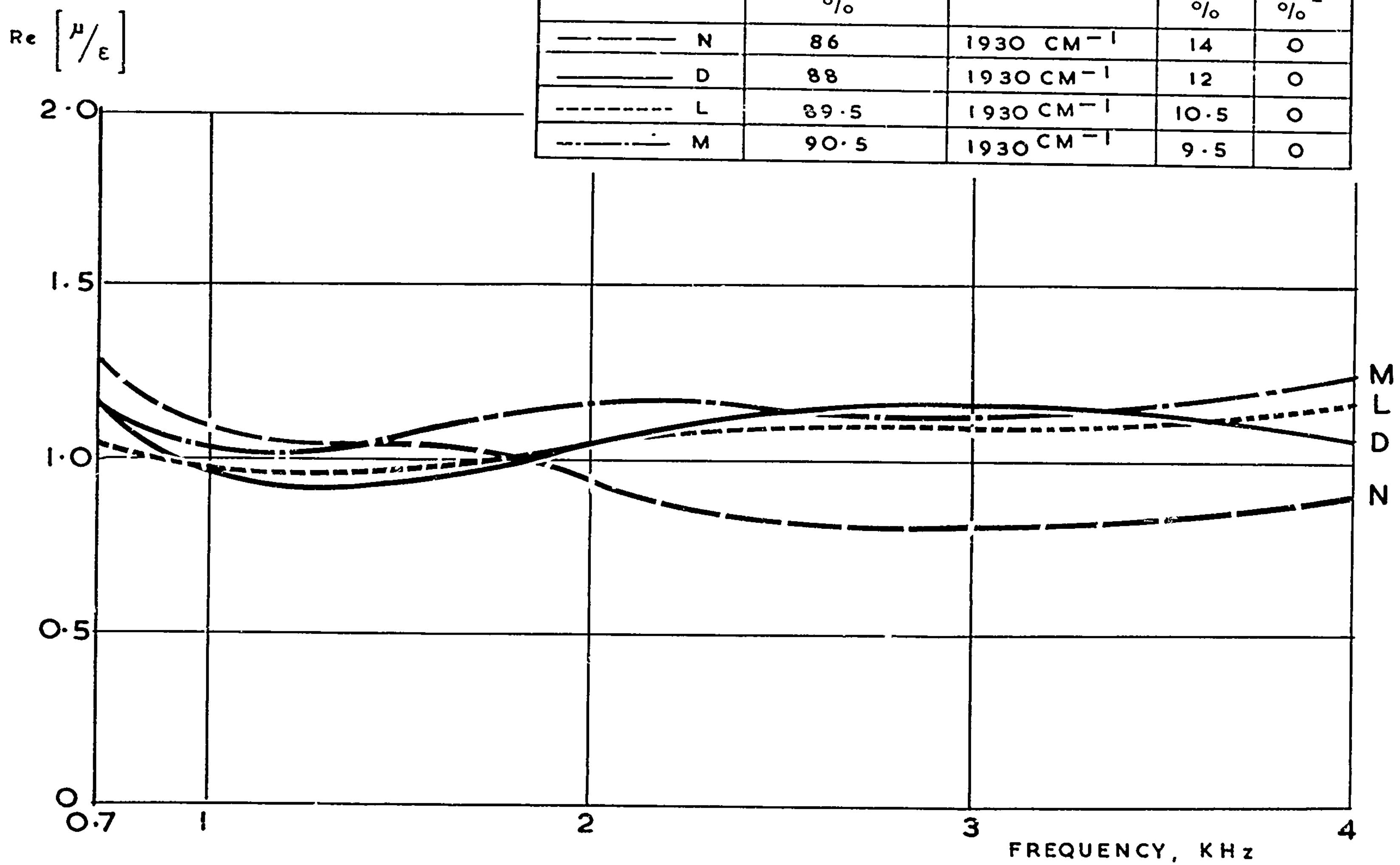
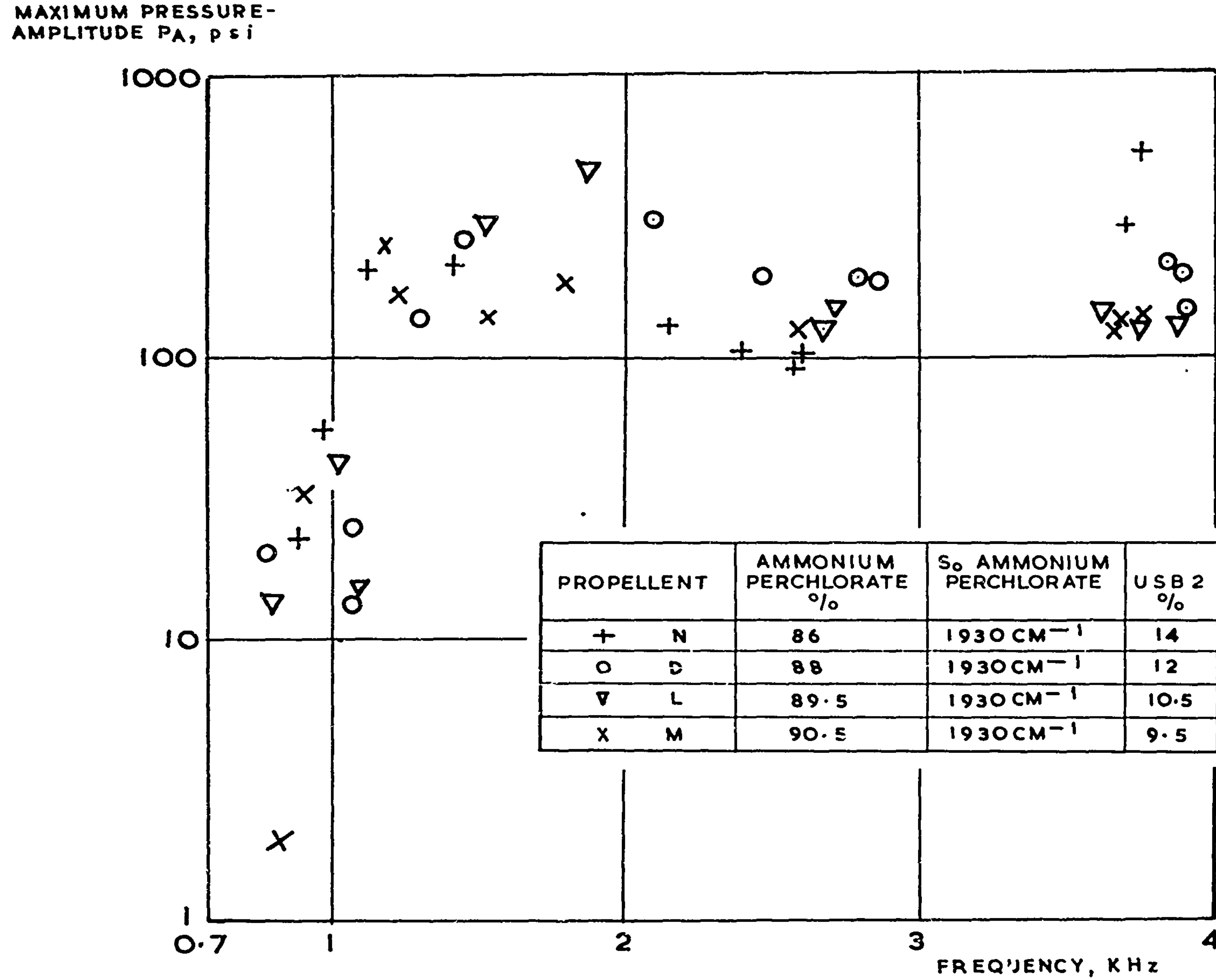


FIG.17 EFFECT OF VARYING THE OXIDISER/FUEL RATIO ON Re$\left[\mu/\varepsilon\right]$ [PROPELLENTS N,D,L,M]



PROPELLENT		AMMONIUM PERCHLORATE %	S_o AMMONIUM PERCHLORATE	USB 2 %	TiO_2 %
+	N	86	1930 CM^{-1}	14	0
o	D	88	1930 CM^{-1}	12	0
▽	L	89·5	1930 CM^{-1}	10·5	0
x	M	90·5	1930 CM^{-1}	9·5	0

FIG. 18 EFFECT OF VARYING THE OXIDISER/FUEL RATIO ON THE MAXIMUM PRESSURE-AMPLITUDE [PROPELLENTS N,D,L,M]

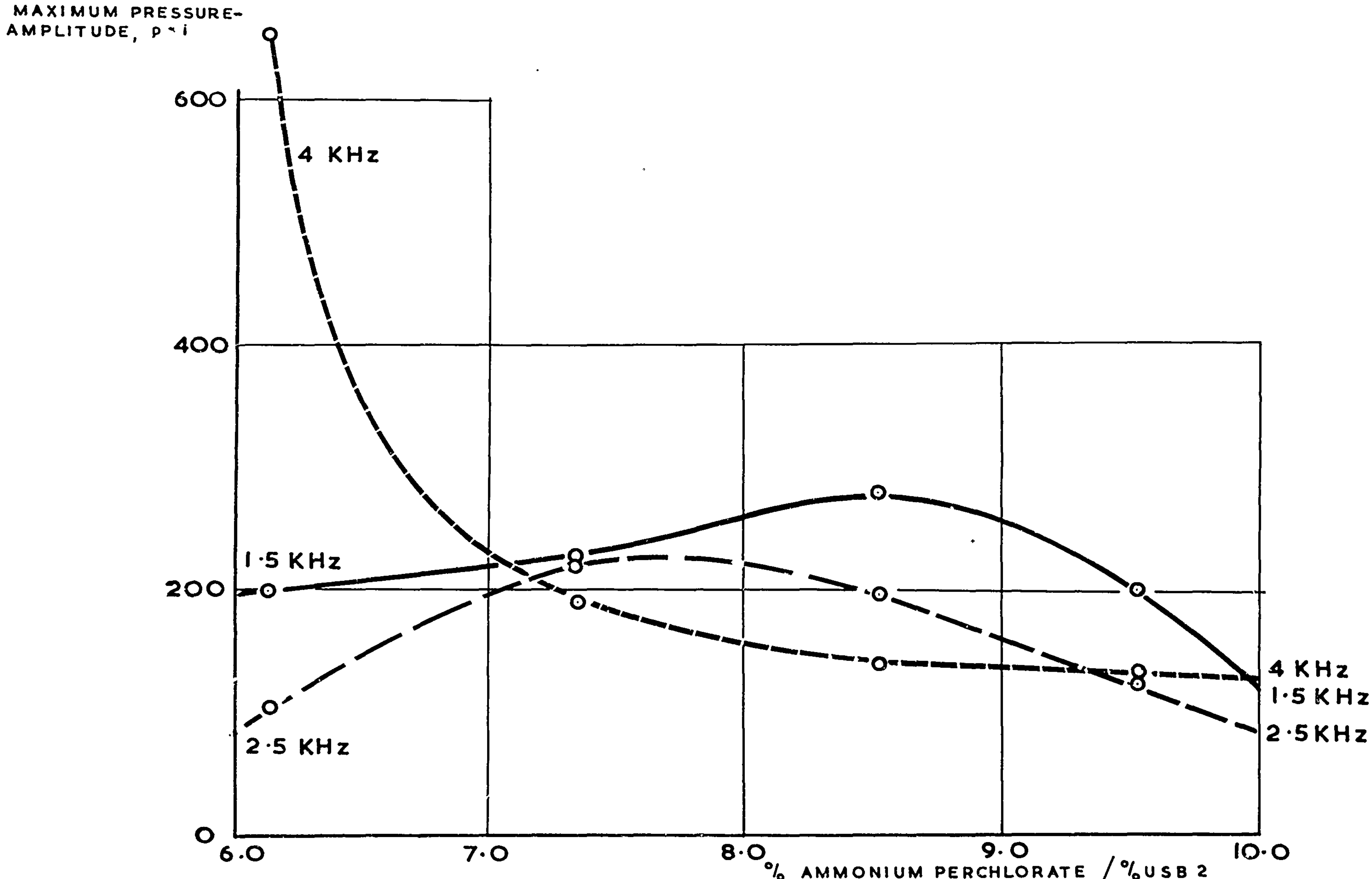


FIG. 19 EFFECT OF FREQUENCY ON THE MAXIMUM PRESSURE-AMPLITUDE REACHED FOR PROPELLENTS WITH DIFFERENT OXIDISER / FUEL RATIOS [PROPELLENTS N,D,L,M]

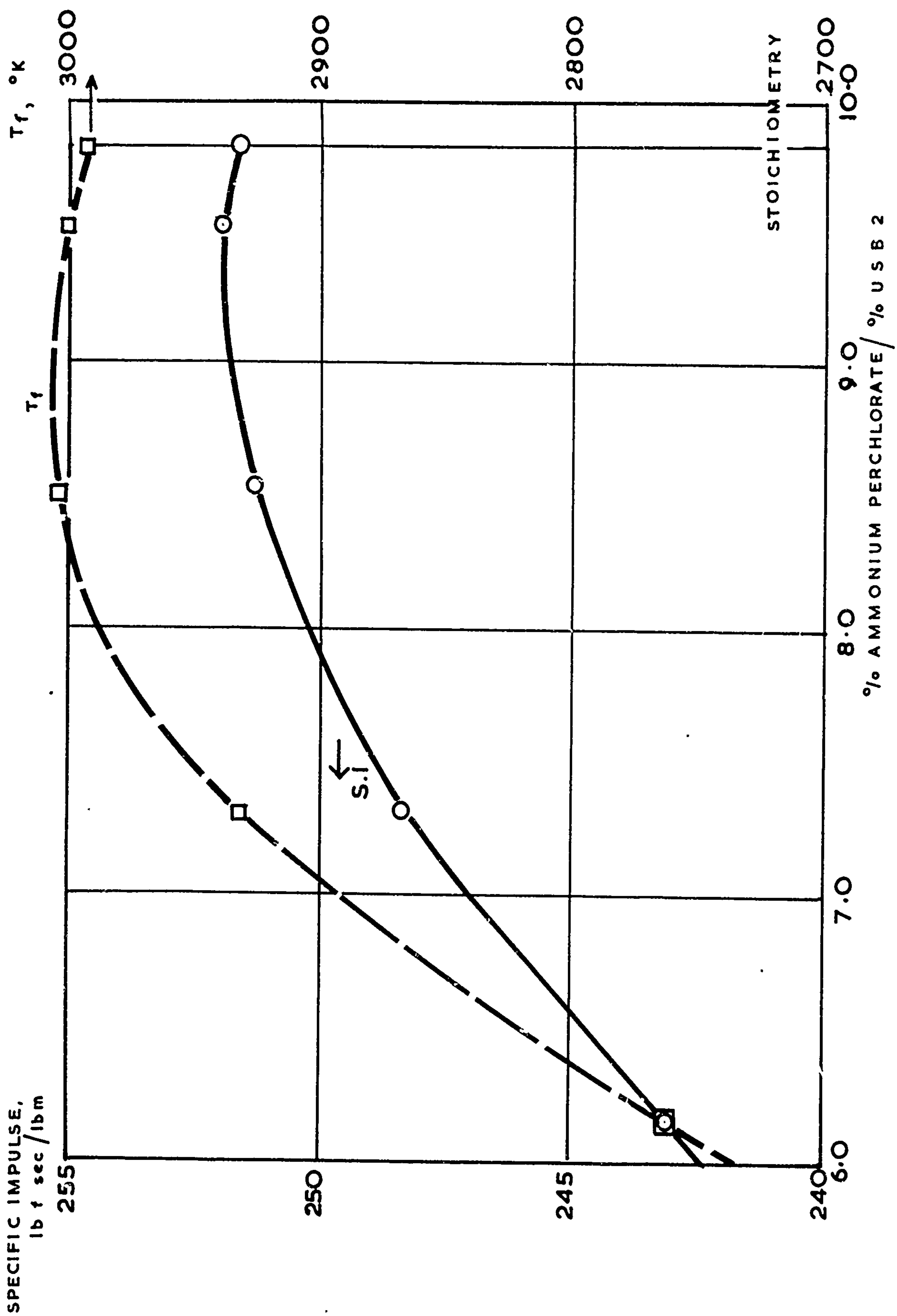


FIG. 20 EFFECT OF OXIDISER/FUEL RATIO ON FLAME TEMPERATURE AND SPECIFIC IMPULSE AT 1000 psi [6895 KN/m²]